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Initial Microstructural Evolution during Friction Stir Welding

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Introduction: Friction stir welding (FSW) has become an important new technique for joining aluminum alloys. In FSW, a rotating tool is plunged into the solid metal, heating it sufficiently (without melting) that the surrounding metal can be "stirred" together into a solid joint. Despite the commercial success of this technique, many fundamental aspects of this welding process remain poorly understood. To address this lack of understanding, we have made the first-ever friction stir welds in a single crystal and quenched the end of the weld to "freeze-in" a static representation of the dynamic deformation field surrounding the tool. The single crystal starting material ensures that the FSW process is directly responsible for all the grain boundary generation and crystallographic texture evolution observed in the weld (except that from conventional recrystallization). Thus, this study is uniquely designed to reveal the initial stages of grain boundary development and texture evolution that occur during FSW.

The Friction Stir Weld Samples: An aluminum single crystal was friction stir welded in four different directions for this study (see Fig. 1). Upon completion of the welds, the tool was withdrawn and the end of the weld was immediately quenched in an attempt to preserve the microstructure surrounding the tool. The regions ahead of the welding tool were polished at the plate mid-thickness and examined in a scanning electron microscope using electron backscattered diffraction. This analysis focused on the evolution of grain structure and texture during FSW and thus excluded the large conventionally recrystallized grains, which are not typically observed in friction stir welds.

Texture Evolution: The stirring action of the rotating welding tool introduces a corresponding rotation in the surrounding material, as shown in the pole figures at the bottom of Fig. 2. Small rotations develop in a continuous manner from the original single crystal orientation. These rotations continue until a specific terminal orientation, indicated with a star, is achieved. This terminal orientation aligns the {111} crystal planes, which are the most densely packed planes and thus the planes along which slip occurs, with the shear plane of the deformation field. For this weld, a rotation of about 50° was required to align these planes. Once the {111} planes are aligned with the shear field, further deformation can be accommodated by repeated slip of those planes without the necessity for any further crystal rotation. This texture evolution was observed in all the weld orientations.

The texture evolution in a weld made perpendicular to the one discussed above exhibited an additional and surprising characteristic (see Fig. 3). Most of the initial texture evolution was similar to that discussed above, with the pink single crystal orientation evolving towards a darker pink and eventually a blue terminal orientation. However, thin deformation bands with a different pink orientation developed *by rotating counter to the prevailing deformation field* until achieving a green terminal orientation. This counter-rotation aligns the <110> crystal direction, the prevalent slip direction for face-centered cubic materials such as aluminum, along the shear direction of the deformation field.

The texture observed near the tool is characteristic of high-temperature, high-strain deformation of aluminum and has previously been observed in friction stir welds. The severe conditions that produced this texture have also removed any correlation to the texture from which it developed.

Grain Boundary Generation: The deformation introduced during FSW is inhomogeneous, causing

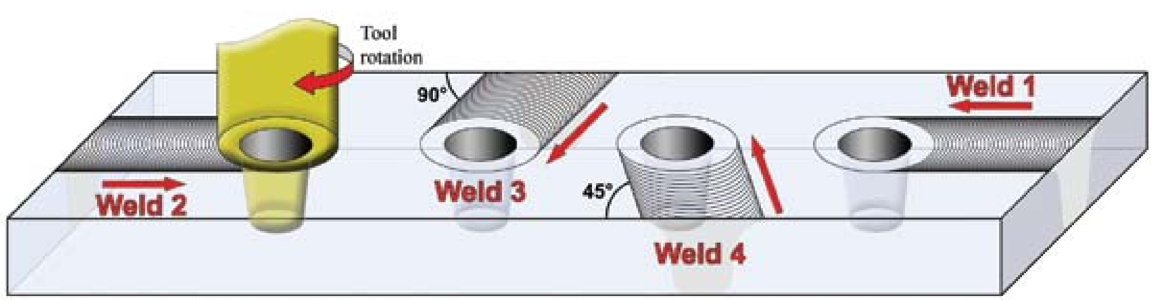

FIGURE 1
Schematic of the FSW process and the four weld orientations examined in this study.

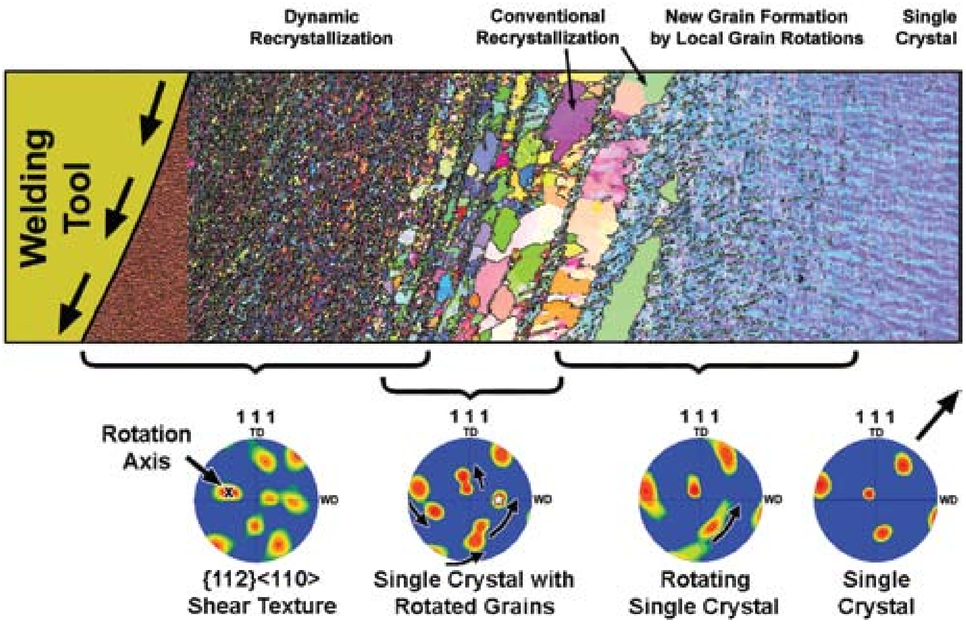

FIGURE 2
Electron backscattered diffraction scan of the region ahead of the tool in Weld 3. Colors represent crystal directions and black lines indicate grain boundaries with at least 15° misorientations. Pole figures at the bottom reveal the crystallographic texture evolution of the small grains; labels at the top indicate different regions of grain/texture evolution.

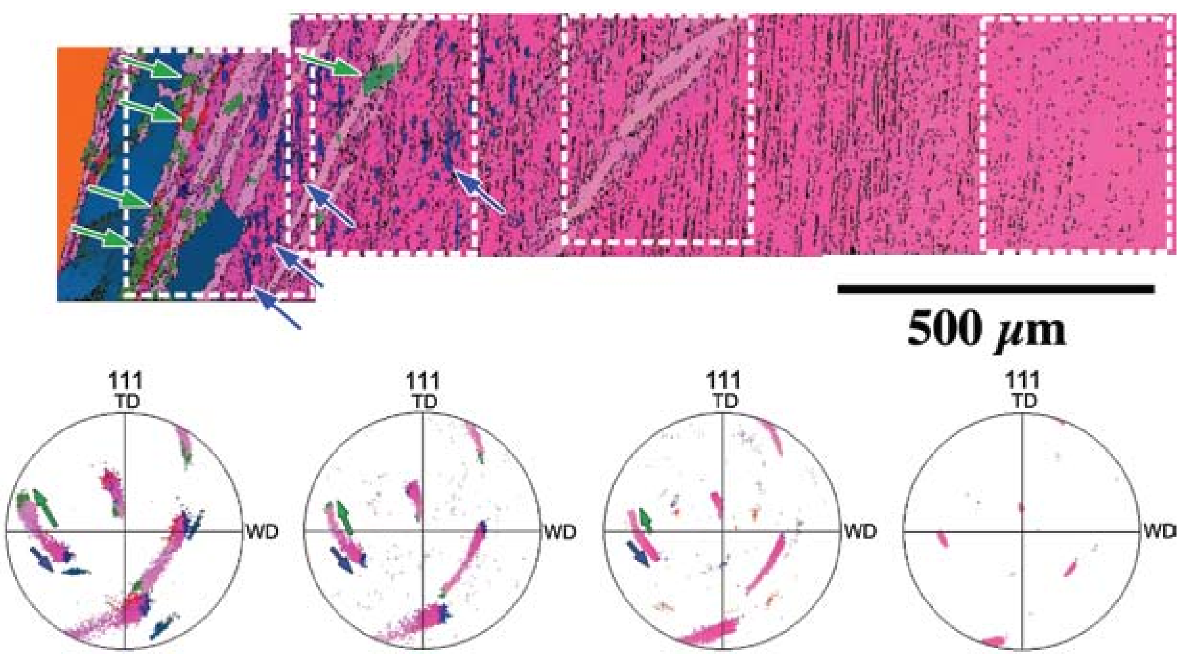

FIGURE 3
Electron backscattered diffraction scan of the outer weld-affected regions ahead of the tool in Weld 2 and pole figures from the boxed regions. Colors indicate orientations and are consistent between image and pole figures, while black lines indicate misorientations ≥15°. Blue arrows indicate terminal orientations from the normal rotation while green arrows indicate the terminal orientations from the counter-rotation.

some regions to rotate relative to others and thus develop misorientations between those regions (see Figs. 2 and 3). These small misorientations give rise to a modulated appearance of the single crystal. The rotated regions continue to develop in both size and misorientation as the tool approaches and the welding deformation increases, generating distinct grains within the single crystal. If these new grains are not already aligned with the shear deformation field (e.g., as in Fig. 2, where the grains are perpendicular to the deformation field), the grains rotate in response to that deformation in order to align with the deformation field.

Summary: This study represents the first-ever investigation of friction stir welds in a single crystal material, and is crucial for understanding the fundamental processes that occur during this welding process. By "freezing-in" the microstructure surrounding the welding tool, we were able to determine the initial mechanisms of texture evolution and grain boundary development that occur during FSW. The shear deformation generated by the welding process gradually rotates regions of the single crystal, which grow in size and misorientation as the welding deformation continues. This rotation continues until these new grains achieve an easily-sheared orientation. Some regions of the weld may even rotate counter to the prevailing deformation field in order to achieve such an orientation. As the tool advances, the new grains gradually rotate to align with the deformation field.

Further development of this grain structure and texture has been obscured by conventional recrystallization and severe deformation near the tool. Additional studies are required to determine the processes of grain boundary evolution and texture evolution that occur after these initial stages.

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